

High Energy Phenomena in Blazars

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Abstract. Advances in the capabilities of X-ray, gamma-ray and TeV telescopes have brought new information on the physics of relativistic jets, which are responsible for the blazar "phenomenon". In particular the broad band sensitivity of the *BeppoSAX* satellite, extending up to 100 KeV has allowed unprecedented studies of their hard X-ray spectra. I summarize here some basic results and present a unified view of the blazar population, whereby all sources contain essentially similar jets despite diversities in other properties, like the presence or absence of emission lines in their optical spectra. Blazars with emission lines are of particular interest in that it is possible to estimate both the luminosity of the jet and the luminosity of the accretion disk. Implications for the origin of the power carried by relativistic jets, possibly involving rapidly spinning supermassive black holes are discussed. We suggest that emission line blazars are accreting at near critical rates, while BL lacs, where emission lines are weak or absent are highly subcritical.

INTRODUCTION

The original argument which led to hypothesize supermassive black holes as basic engines for the AGN phenomenon (Zeldovich & Novikov 1964; Salpeter 1964) was extremely "simple". A source of high luminosity which varies rapidly must be very "compact" : since its size R must be less than ct_{var} the photon density $L/(4\pi R^2 c)$ is extremely high. A source of high compactness (defined in adimensional terms as $l = L\sigma_T/Rmc^3$) must be very efficient as shown most clearly by Fabian (1979) who derived the well known limit $\Delta L/\Delta t \lesssim \eta 10^{43} \text{ erg/sec}^2$, where η is the radiative efficiency. Accretion onto black holes can be orders of magnitude more efficient than ordinary nuclear reactions powering stars, with η up to 42% (e.g., Rees 1984) but still limited to values < 1 .

Thus there is a maximum compactness that any source powered by accretion cannot exceed. However observationally some AGN violate even this limit. Early results concerned the excessive brightness temperatures inferred from the variability of compact radio sources. More recently, the observation of gamma-rays varying rapidly, from the same class of sources exhibiting the fast radio variability, provided new independent evidence of violation of the fundamental compactness limit (Maraschi et al. 1993). For this relatively small fraction of AGN, called blazars, relativistic motion of the emitting plasma has been invoked in order to reconcile the observed properties with basic physics (Blandford and Rees, 1978).

It is now generally accepted that the blazar "phenomenon" (highly polarised and rapidly variable radio/optical continuum) is due to a relativistic jet pointing close to the line of sight. An additional step towards unification is to propose that jets are basically similar in all blazars, despite diversities in other properties, most notably the presence

or absence of emission lines in their optical spectra (flat spectrum quasars (FSQ) vs. BL Lacs). This hypothesis was put forward by Maraschi & Rovetti (1994) on the basis of the "continuity" of the radio and X-ray luminosity functions of the two classes of blazars.

Here I will follow the point of view that Quasars with Flat Radio Spectrum (FSQs, which include OVV's and HPQs) and BL Lac objects belong to a single population, in the sense that the nature of the central engine is similar apart from differences in scaling. The plan is to start from a physical comprehension of the phenomenology common to all blazars, in particular of the broad band spectral energy distributions (SEDs) from radio to γ -rays, with the goal of understanding eventually the role of more fundamental parameters, like the central black hole mass, angular momentum and accretion rate, in determining the properties of the jets and of the associated accretion disks.

THE UNIFIED FRAMEWORK FOR THE SEDS OF BLAZARS.

It was noted early on that the SEDs of blazars exhibit remarkable systematic properties (Landau et al. 1986, Sambruna et al. 1996). The subsequent discovery by the Compton Gamma Ray Observatory of gamma-ray emission from blazars (a summary can be found in Mukherjee et al. 1997) was a major step forward, showing that in many cases the bulk of the luminosity was emitted in this band and questioning the importance of previous studies of the SEDs at lower frequencies.

A systematic investigation on the SEDs of the main complete samples of blazars (X-ray selected, radio-selected and Quasar-like, Fossati et al. 1998) including gamma-ray data showed that the systematic trends found previously indeed persisted, suggesting a continuity of spectral properties (spectral sequence). A suggestive plot where sources from different complete samples have been grouped in radio-luminosity decades (see Fossati et al. 1998 for a full description) is shown in Fig. 1.

All the SEDs show two broad components with peaks in the $10^{13} - 10^{18}$ Hz and $10^{21} - 10^{25}$ Hz ranges respectively. Both peaks appear to shift to higher frequencies with decreasing luminosity. We will call red and blue the objects respectively at the low and high frequency extremes of the sequence.

Beamed synchrotron and inverse Compton emission from a single population of relativistic electrons accounts well for the first and second peak respectively in the observed SEDs. Note that the relativistic particle spectrum must be "curved" in order to explain the peaks observed in the SEDs. The curvature is often modelled with a broken power law. The change in spectral index must be quite large to explain the emission peaks and the energy, γ_b , at which the change (or break) occurs corresponds to the energy of electrons which radiate at the peak.

Homogenous models fail however to reproduce the SEDs in the radio to mm range, where selfabsorption cuts off the contribution of the electron population accounting for the higher energy emission (see also Kubo et al. 1998). In fact it is well known that at low frequency the observed spectra are due to the superposition of different components located further down the jet, with selfabsorption turnover at lower and lower frequencies (e.g., Konigl 1989). These "external" regions, with scales of the order of parsecs resolved by VLBI observations, are not considered in the present discussion which refers to scales

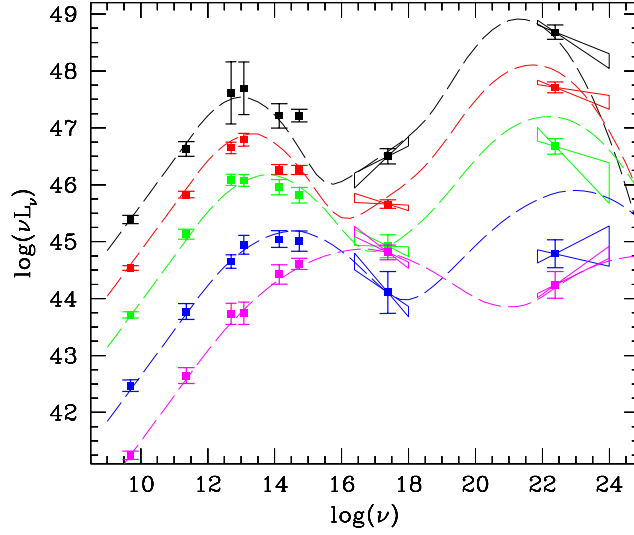


FIGURE 1. Average SEDs of the "merged" blazar sample binned according to radio luminosity, irrespective of the original classification. Empty asymmetric triangles represent uncertainties in spectral shapes as measured in the X-ray and γ -ray bands. The overlaid dashed curves are analytic approximations obtained assuming that the ratio of the two peak frequencies is constant and that the luminosity of the second peak is proportional to the radio luminosity (from Fossati et al. 1998).

of the order of light days or smaller (in the observer's frame).

The homogenous model predicts that the synchrotron and IC emissions should vary in a correlated fashion, since they derive from the same electron population. In particular radiation at frequencies near the two peaks derives from electrons in the same energy interval (in the absence of Klein-Nishina effects) therefore variations in these two "corresponding" frequency ranges should be strongly correlated. This has been verified at least in some well studied objects (see below).

Ghisellini et al. 1998 derived the physical parameters of jets of different luminosities along the spectral sequence shown in Fig. 1 applying the above model and including seed photons of internal (SSC) as well as external (EC) origin for the inverse Compton process. The results suggest that i) the importance of external seed photons increases with increasing jet luminosity ii) the "critical" energy of the radiating electrons decreases with increasing (total) radiation energy density as seen in the jet frame. The latter dependence is physically plausible since the radiation energy density determines the energy losses of relativistic particles and may limit the energy attained by particles in shock acceleration processes.

In a broader perspective, if FSQs and BL Lacs contain "similar" jets (at least close to the nucleus) as suggested by the continuity of the SEDs, we still need to understand the differences in emission line properties. Also in this respect continuity could hold, in the sense that the accretion rate may decrease continuously along the sequence but the emission properties of the disk may not simply scale with the accretion rate.

STUDIES OF INDIVIDUAL OBJECTS.

It is impossible to review here all the important multifrequency studies of selected objects often triggered by flares (e.g. Bloom et al. 1996, Kubo et al. 1998, Tagliaferri et al. 2000, 2001, Sambruna 2000 and references therein,) We discuss below only three cases which are among those with the best data collection and can be considered representative of the behaviour of sources at the red and blue ends of the blazar sequence.

3C 279

This source is a prototype of red blazars and the first one to be discovered as a powerful gamma-ray emitter. Its spectral energy distribution illustrates well the presence of two main continuum components, the first one peaking in the IR, the second one in the gamma-ray range, attributed to the Synchrotron and inverse Compton mechanisms respectively. Two SEDs with simultaneous optical, X-ray and gamma-ray data obtained respectively in 1996 and 1997 are shown in Fig. 2. The 1997 X-ray data derive from observations with *BeppoSAX* (Hartman et al. 2001, Maraschi et al. in preparation). The two SEDs differ largely in brightness: that of 1996 is close to a historical maximum, while that of 1997 is rather faint. Clearly the two components of the SED vary in a correlated fashion (this is confirmed by a handful of other observations with comparable simultaneous multifrequency coverage) and the variability amplitude in the IR-optical branch is much less than at gamma-rays. This was predicted by the SSC model (Ghisellini & Maraschi 1996) but the physical parameters derived using a homogeneous SSC model are inconsistent with the rapid gamma-ray variations observed. Applying the EC model for gamma-ray production yields acceptable parameters. However the photon field surrounding the jet is not expected to vary rapidly except under special conditions (Ghisellini & Madau 1996, Bednarek 1998, Böttcher & Dermer 1998.). The large amplitude variability in gamma-rays can then only be attributed to a variation in the bulk flow velocity as illustrated in Fig 2.

The two spectral states have been reproduced using the same theoretical model (e.g. Tavecchio et al. 2000) varying only the bulk Lorentz factor Γ of the emitting plasma (Maraschi et al. 2001 in prep). The contributions of synchrotron photons and of external photons to the Inverse Compton emission are shown separately (dot dashed and dashed lines respectively). While this picture is probably still oversimplified, it fits nicely with a recently proposed scenario derived from the "internal shock" model developed for Gamma-Ray Bursts. In the latter (Spada et al. 2001, in press), most of the variability is attributed to the collisions of plasma sheaths moving along the jet with different Γ s. This scenario is very promising for explaining the full range of variability of 3C 279.

For red blazars the study of the synchrotron component is difficult, because the peak falls in the poorly covered IR - FIR range. Furthermore the study of the gamma-ray component in the MeV-GeV region of the spectrum has been difficult in the last few years due to the loss of efficiency of EGRET and is now impossible after reentry of CGRO. Substantial progress will have to await the launch of new gamma-ray satellites, like AGILE planned by the Italian Space Agency (ASI) and GLAST by NASA.

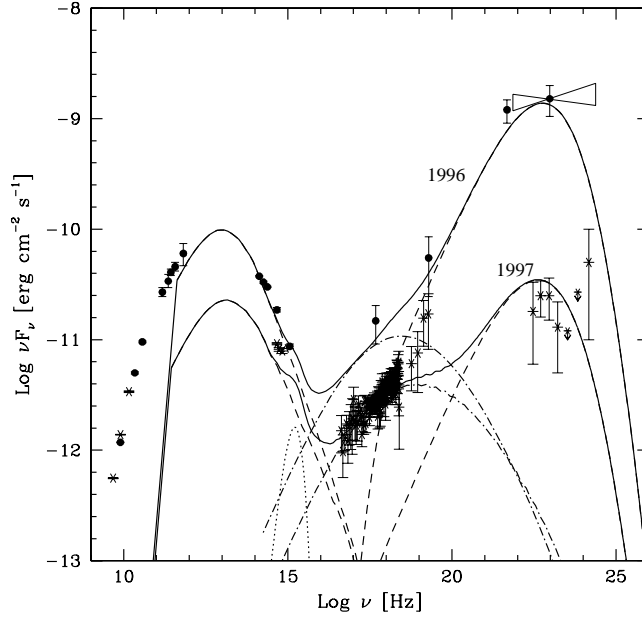


FIGURE 2. Quasi-simultaneous SEDs of the quasar 3C279 obtained at two epochs 1996 and 1997. The 1996 SED represents a historical maximum. The X-ray data of 1997 were obtained with *BeppoSAX*. The continuous lines represent synchrotron plus Inverse Compton models computed to reproduce the observations at the two epochs (see text). For both epochs subcomponents of the Inverse Compton emission are shown as dot-dashed (SSC) and dashed (EC) lines respectively. The dotted component is a Blackbody approximating the estimated emission from an accretion disk, assumed to be constant. The models for the two epochs differ mainly in the value of Γ_{bulk}

Mkn 501, Mkn 421

In the last years high energy observations have concentrated on blue blazars. For several sources of this class the Synchrotron component peaks in the X-ray band, where numerous satellites can provide good data. In few bright extreme BL Lac objects the high energy γ -ray component is observable from ground with TeV telescopes (for a general account see Catanese & Weekes 1999). In these particular cases the contemporaneous X-ray/TeV monitoring demonstrated well the correlation between the Synchrotron and the IC components. Dramatic TeV flares exhibited by Mkn 501 were accompanied by exceptional outbursts in X-rays where *in the brightest state the peak of the synchrotron spectrum reached 100 KeV* as observed by *BeppoSAX* (Pian et al. 1998). Similar behaviour was observed with RXTE (Sambruna et al. 2000, Catanese & Sambruna 2000).

Another important case is that of Mkn 421 for which a rapid flare (timescale of hours) was observed simultaneously in the TeV and X-ray bands by the Whipple observatory and by the *BeppoSAX* satellite in 1998. This observation probed for the first time the existence of correlation on short time scales (Maraschi et al. 1999). An associated intensive multiwavelength campaign (involving EUVE ASCA RXTE and the CAT, HEGRA and Whipple observatories) organized by Takahashi showed that TeV variations

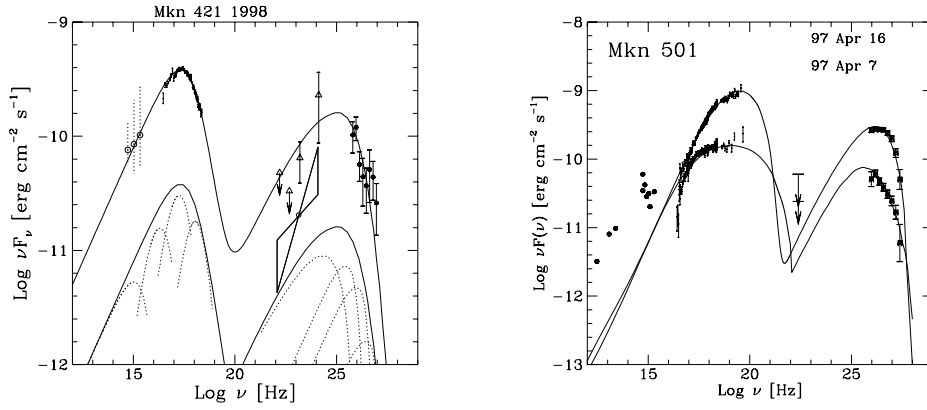


FIGURE 3. *Left:* Overall SED of Mkn 421 obtained from observations taken in 1998 April (from Maraschi et al. 1999). The X-ray and TeV data are exactly simultaneous. The solid line is the spectrum computed with the SSC model. Below the actual model, subcomponents due to electrons in 4 fixed energy intervals are shown both for the synchrotron and SC processes. *Right:* Overall SED of Mkn 501 observed simultaneously by *BeppoSAX* and CAT during the major flare in April 1997 (From Tavecchio et al. 2000, in press). The solid lines are the spectra computed with the SSC model. The models for the high and low state differ only in the value of $\gamma_b mc^2$, the energy of the electrons radiating at the peak of the synchrotron component. For both sources the observational constraints on the two peaks allow to obtain robust estimates of the physical parameters of the jet.

correlate with X-rays also on longer timescales and confirmed the trend of spectral hardening with increasing X-ray intensity (Takahashi et al. 1999).

When the position of the synchrotron and SSC peaks can be well determined observationally, as is possible in this type of sources, robust estimates of the physical parameters of the jet can be obtained (e.g. Tavecchio et al. 1998). This was done for both Mkn 421 and Mkn 501 as illustrated in Fig. 3 (Maraschi et al. 1999, Tavecchio et al., in press). For Mkn 421 subcomponents due to electrons in 4 fixed energy intervals are shown in Fig. 3 both for the synchrotron and SSC process, in order to give an intuitive view of the correlation between different energy ranges. Note for Mkn 501 the definite change in the TeV spectra measured by the CAT group (Djannati-Atai et al. 1999) indicating a shift of the IC peak consistent with the change of the X-ray spectrum.

As a result of these model fits to different states with the simultaneous constraint on the X-ray and TeV spectra, we can confidently deduce that the flares are due to an increase of the critical electron energy γ_b rather than to a variation of the bulk Lorentz factor Γ as suggested for 3C279. These "modes" of variability may represent a significant difference between red and blue blazars.

JET POWER VS. ACCRETION POWER

We now turn to discuss luminous blazars with emission lines. These fall at the high-luminosity end of the sequence, with the Synchrotron peak in the FIR region. In these

sources the beamed X-ray emission is believed to be produced through IC scattering between soft photons external to the jet (produced and/or scattered by the Broad Line Region) and *relativistic electrons at the low energy end of their energy distribution*. It is important to stress that the broad band sensitivity of *BeppoSAX* allowed to measure the X-ray spectra from 0.3 up to 100 KeV for a number of these objects. Note that for this type of sources the hard X-ray emission has luminosity comparable to that measured in gamma-rays, due to the fact that the EC peak falls in between the two ranges.

Measuring the X-ray spectra and adapting a broad band model to their SEDs yields reliable estimates of the total number of relativistic particles involved, which is dominated by those at the lowest energies. This is interesting in view of a determination of the total energy flux along the jet (e.g. Celotti et al. 1997, Sikora et al. 1997). The total "kinetic" power of the jet can be written as:

$$P_{\text{jet}} = \pi R^2 \beta c U \Gamma^2 \quad (1)$$

where R is the jet radius, Γ is the bulk Lorentz factor and U is the total energy density in the jet, including radiation, magnetic field, relativistic particles and eventually protons. If one assumes that there is 1 (cold) proton per relativistic electron, the proton contribution is usually dominant.

In high luminosity blazars the UV bump is often directly observed and/or can be estimated from the measurable emission lines, yielding direct information on the accretion process in the hypothesis that the UV emission derives from an accretion disk. *Thus the relation between accretion power and jet power can be explored*. This approach was started by Celotti et al. (1997) but their estimates of P_{jet} were obtained applying the SSC theory to VLBI radio data which refer to pc scales, much larger than the region responsible for the high energy emission ($10^{-2} - 10^{-3}$ pc).

We took advantage of *BeppoSAX* data for a number of emission line blazars deriving their jet powers as described above. The SEDs for three objects together with the models computed to represent the data are shown in Fig 4 (from Tavecchio et al. 2000). We have preliminary results for 6 other sources with similar characteristics, all observed with *BeppoSAX*. We further consider blazars with less prominent emission lines, for which we had previous good quality *BeppoSAX* and multifrequency data, namely 3C 279, BL Lac, ON231 (Tagliaferri et al. 2001, Tagliaferri et al. 2000) plus Mkn 501 and Mkn 421 discussed above.

In all cases we estimated physical parameters by means of a homogeneous SSC+EC model and derived accordingly the kinetic power of the jet including 1 cold proton per electron, P_{jet} , as well as the total luminosity radiated by the jet in the observer frame (L_{jet}). The luminosity of the disk could be estimated for all objects except the latter three BL Lac, for which we could set only upper limits on the luminosity of their putative accretion disks. For 3C 279 and BL Lac, the presence of broad $\text{Ly}\alpha$ and $\text{H}\alpha$ respectively allowed to estimate the ionizing continuum (e.g. Corbett et al. 2000).

In Fig 5a the derived radiative luminosity L_{jet} and kinetic power of the jet P_{jet} are compared. The ratio between these two quantities gives directly the "radiative efficiency" of the jet, which turns out to be $\eta \simeq 0.1$, though with large scatter. The line traces the result of a least-squares fit: we found a slope ~ 1.3 , indicating a decrease of the radiative efficiency with decreasing power.

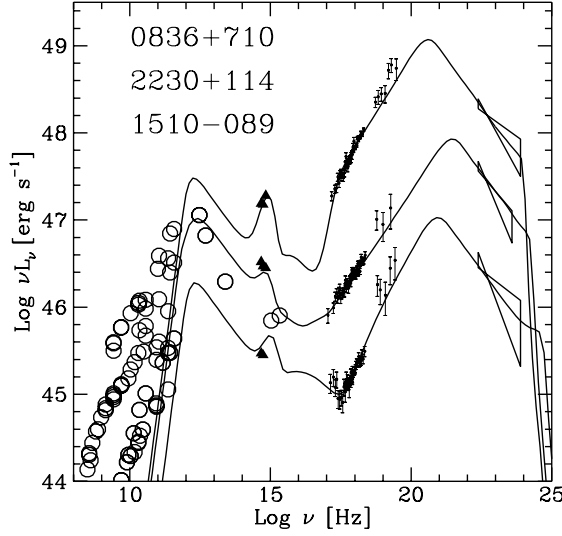


FIGURE 4. Overall SEDs of three powerful emission-line Blazars (from Tavecchio et al. 2000). The continuous lines are theoretical models computed to account for the jet emission, plus a blackbody component. The objects are characterized by the presence of a strong UV-bump, allowing the determination of the luminosity of the accretion disk as well as the luminosity and power of the jet from the model fits to the non thermal emission.

In Fig. 3b we compare the luminosity of the jet, L_{jet} , which is a *lower limit* to P_{jet} , with the luminosity of the disk, L_{disk} .

A first important result is that on average the minimal power transported by the jet is *of the same order* as the luminosity released in the accretion disk. This result poses an important constraint for models elaborated to explain the formation of jets.

Two main classes of models consider either extraction of rotational energy from the black hole itself or magnetohydrodynamic winds associated with the inner regions of accretion disks. Let us parametrize the two possibilities as follows. Blandford & Znajek (1977) summarize the result of their complex analysis of extraction of rotational energy from a black hole in the well known expression:

$$P_{\text{BZ}} \simeq B_0^2 r_g^2 a^2 c \quad (2)$$

Assuming maximal rotation for the black hole ($a = 1$), the critical problem is the estimate of the intensity reached by the magnetic field threading the event horizon, which must be provided by the accreting matter. Using a spherical free fall approximation with $B_0^2/8\pi \simeq \rho c^2$ one can write:

$$P_{\text{BZ}} \simeq g \dot{M} c^2 \quad (3)$$

where $P_{\text{acc}} = \dot{M} c^2$ is the accretion power and g is of order 1 in the spherical case, but in fact it is a highly uncertain number since it also depends on the field configuration.

Several authors have recently discussed this difficult issue in the case of an accretion disk: the arguments discussed by Ghosh & Abramovitz (1997) (GA; see also Livio, Ogilvie & Pringle 1999) plus equipartition within an accretion disk described by the Shakura and Sunyaev (1973) model lead to $g \simeq 1$ when gas pressure dominates. However at high accretion rates, when radiation pressure dominates, the pressure and consequently the estimated magnetic field do not increase further with \dot{M} but saturate at the transition value. The estimates of P_{BZ} derived by GA for various values of the mass of the central black hole are compared with the values of L_{jet} and L_{disk} in Fig 5b. The accretion rate which appears in the formulae of GA has been converted into a disk luminosity using an efficiency $\epsilon \simeq 0.1$, while 100% radiative efficiency has been assumed for the jet. Clearly the model fails to explain the large power observed in the jets of bright quasars, even for BH masses ($M \sim 10^9 M_\odot$). Different hypotheses on the structure of the flow near the black hole, for instance frame dragging by the rotating hole may however increase g to values even larger than 1 (Meier 1999, Krolik 1999; Acceleration and collimation of cosmic jets (session 6), this volume).

As argued by Livio et al. the accretion flow itself may power jets through a hydro-magnetic wind. However for consistency only some fraction $f\dot{M}c^2$ can be used to power the jet. Further recall that the luminosities observed from the jet and disk are related to their respective powers by efficiency factors $L_{jet} = \eta P_{jet}$; $L_{disk} = \epsilon P_{acc}$.

Using the condition that $P_{jet} \leq (P_{BZ} + fP_{acc})$ together with the previous relations we finally find

$$L_{jet} \leq \frac{\eta(g+f)}{\epsilon} L_{disk}. \quad (4)$$

The data we have used suggest $L_{jet} \simeq L_{disk}$ at high luminosities and $L_{jet} > L_{disk}$ at intermediate and low luminosities.

At the high luminosity end the observed luminosities are extremely large. For a disk luminosity of $10^{47} \text{ erg s}^{-1}$ a mass of $10^9 M_\odot$ is implied if the disk is close to the Eddington luminosity, which corresponds to an accretion rate of $10 M_\odot \text{ y}^{-1}$ for $\epsilon = 10^{-1}$. It seems then implausible that such disks could be low efficiency radiators. Assuming that $\eta = 10^{-1}$ as estimated above (Fig 5a), the near equality of L_{jet} and L_{disk} requires g or f or both to be of order 1.

On the other hand, a dominance of L_{jet} over L_{disk} at lower luminosities could be attributed to a lower value of $\epsilon \ll 0.1$ which may be expected if the accretion rate is largely sub-Eddington (e.g., Blandford 1990). In the latter case the range in luminosities spanned by Fig 5b should be mainly a range in accretion rates rather than a range in black hole masses. For instance the minimum jet powers of three of the BL Lacs in Fig 5b are around 10^{44} erg/s which suggests $P_{jet} \simeq 10^{45}$ requiring a mass of 10^7 for critical accretion rate. Since the disk luminosity is less than 10^{42} , if the accretion rate is 1% Eddington the implied mass is again $10^9 M_\odot$. This scenario is attractive (see also Cavaliere & Malquori 1999) and could be verified observationally if the mass of the central object can be determined independently. In fact for low luminosity objects the velocity dispersion close to the core of the galaxy, indicative of the central black hole mass (e.g. Ferrarese et al. 2000) should be measurable.

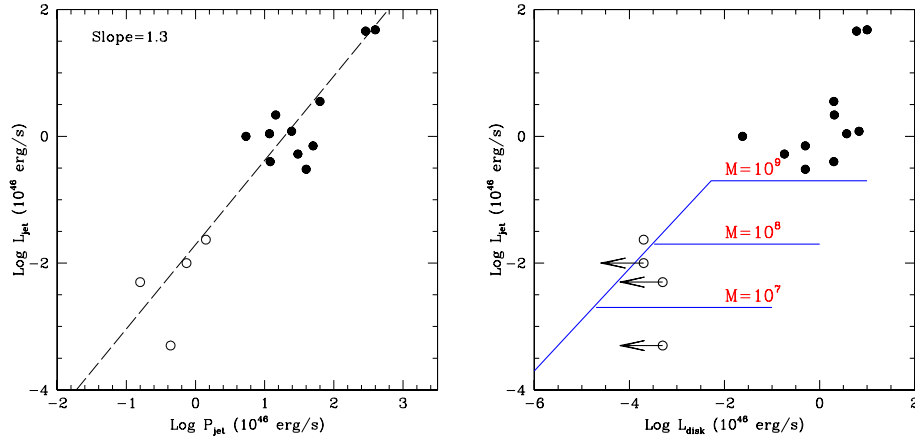


FIGURE 5. *Left:* Radiative luminosity vs. jet power for the sample of Blazars discussed in the text (open circles represent BL Lac objects). The dashed line indicates the least-squares fit to the data. *Right:* Radiative luminosity of jets vs disk luminosity. The solid lines represent the *maximum* jet power estimated for the Blandford & Znajek model for black holes with different masses (in Solar units).

CONCLUSIONS

The study of blazars yields unique information on the physical conditions and emission processes in relativistic jets. A unified approach is possible whereby the jets in all blazars are similar and their power sets the basic scale. While the phenomenological framework is suggested to be "simple" (e.g. "red" blazars are highly luminous, have low average electron energies and emit GeV gamma-rays while "blue" blazars have low luminosity, high average electron energies and emit TeV gamma-rays) we do not yet know what determines the emission properties of jets of different power nor what determines the jet power in a given AGN. We suggest that the basic parameter may be the accretion rate rather than the black hole mass that is all blazars contain very massive black holes and the lower luminosity ones are accreting at sub-Eddington rates. An observational verification of this hypothesis may come from black hole mass determinations in the nearest, lowest luminosity BL Lacs.

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